Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis - I

D.V. Holliday
BAE SYSTEMS
Applied Technologies, IES/ITS
Analysis and Applied Research
4545A Viewridge Avenue
San Diego, CA 92123
phone: (858) 278-5269 fax: (858) 569-0387 email: van.holliday@gso.uri.edu

C.F. Greenlaw
BAE SYSTEMS
Applied Technologies, IES/ITS
Analysis and Applied Research
4545A Viewridge Avenue
San Diego, CA 92123
phone: (830) 372-3239 fax: (858) 569-0387 email: cfgreenlaw@alumni.utexas.net

Contract Number: N00014-00-D-0122 / 3
http://buinne.soest.hawaii.edu:8080/loco2006
http://www.gso.uri.edu/criticalscales

LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

OBJECTIVES

Our near-term objectives during FY 2007 were focused on completion of our 2006 field work. Working with researchers from several different institutions, we have been studying layered organization in the coastal ocean (LOCO). Our most recent field project involved deploying, and maintaining an array of oceanographic sensors at a fixed shallow water site in the northeastern corner of Monterey Bay, CA during the late summer and early fall of 2006. Our first objective was to make available to the LOCO research team as much information as we could in near real-time regarding the presence of thin mesozooplankton layers and their vertical location in the water column. Rapid access to these data allowed LOCO team members to make informed decisions regarding their own sampling protocols as they collected data describing other factors that may influence the growth, lifetime and decay of these thin vertical biological structures. As a secondary objective, we deployed several advanced acoustical sensors for which we did not require real-time access to the data. By increasing the number of frequencies at which acoustic backscattering was measured, one of these sensors improved the size resolution we could achieve in describing the mesozooplankton. We also deployed two sensors with the intent of detecting very small gas bubbles. One was used to examine depths at which thin phytoplanton layers were present in water column, and the other was used to study the top few mm of the shallow, sandy seabed. We were testing a hypothesis that photosynthesis could create

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis - I**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **BAE SYSTEMS Applied Technologies, IES/ITS Analysis and Applied Research 4545A Viewridge Avenue San Diego, CA 92123**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

conditions that would lead to the formation of small bubbles on the phytoplankon in thin layers. Alternatively, if such bubbles were formed in the top few mm of the seabed, broke loose and rose through the water column, they would necessarily have to pass through any thin layer that was present. If such bubbles adhere to phytoplankton cells, strands, mats, or they become embedded in marine snow, then bubbles from either source might act to slow the natural sinking process that removes marine algae from the euphotic zone. The same sensor is useful in examining the water column for depths where larval, swimbladder-bearing fish aggregate.

Both of the BAE Systems principal investigators involved in LOCO retired during the first half of FY 2007. They are continuing this project, participating in the ongoing LOCO data synthesis work under a grant to the University of Rhode Island (URI). This report covers the period from October 2006 through Feburary 2007. Progress from April 2007 through the end of FY 2007 is covered in a companion report for the grant to URI.

APPROACH

During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, nutrients, and physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in northeastern Monterey Bay. Other team members examined larger scale horizontal distributions and temporal thin layer patterns in deeper water nearby, while still others collected plankton and made measurements of turbulence and various optical properties of the water column. Our part of this research involved the deployment of several acoustic sensors on the seabed. Some of these sensors were employed as up-looking multiple-frequency echo sounders in this study (Fig. 1). In order to gain some idea of the spatial extent and temporal coherence of thin layer structures, our instruments were placed *ca*. 100 m apart in an array of other LOCO sensors near the 20 m contour just off Aptos, CA.

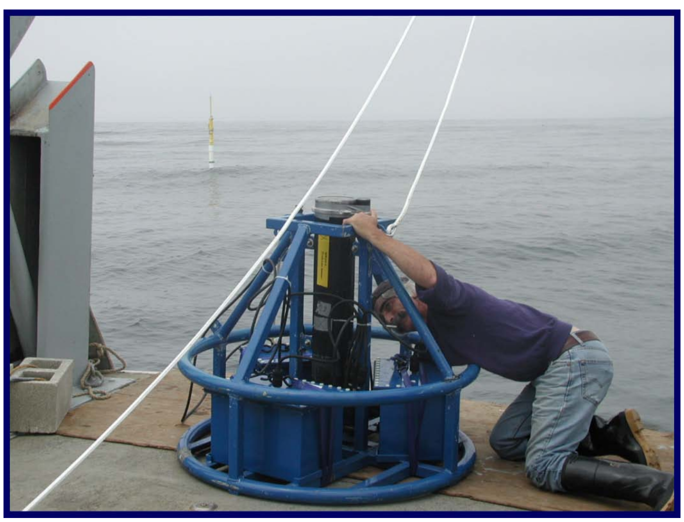

Figure 1: A TAPS-6 acoustical sensor is shown prior to its deployment at a station ca. 3.5 km SSW of Aptos, CA, near the 20 m depth contour. In this cage, a six frequency TAPS is mounted vertically (black cylinder). The LOCO sampling protocol required the TAPS to be configured as an up-looking echo sounder. A spar buoy can be seen floating in the distance. Data and power are transferred to a two-way VHF radio in the buoy via an electrical cable connected to the TAPS. Several key system parameters are programmable and were controlled from a shore station as needed.

The acoustic frequencies used in one of the sensors, the TAPS-6, were 0.265, 0.420, 0.700, 1.100, 1.850 and 3 MHz. These frequencies have previously been shown to span critical structure in the volume scattering strength spectrum of small zooplankton (Holliday and Pieper 1980). This allows one to estimate scatterer sizes and abundances above the sensor as a function of depth and time (Holliday 1977). Thin layers were tracked in depth as they responded to external physical stimuli (e.g., light, the passage of internal waves, tidal forcing) and plankton behavior was observed as the layer moved vertically, presumably in search for food (e.g., phytoplankton or microzooplankton). We have also observed what appears to be avoidance of particular depths when various toxins are present in the phytoplankton (e.g., harmful algal blooms (HABs). Observations can also be made of the aggregation of predators (e.g., fish) on thin layers, although a higher repetition rate would be needed to track foraging by individual fish. The vertical resolutions of these sensors are *ca*. 12.5 cm. By employing two-way telemetry we were able to adapt our temporal sampling rates to quickly respond to the observed acoustic scattering patterns. When we needed very high-resolution data rates in order to avoid aliasing we used sampling intervals as short as 30 sec. During most of the deployment period we sampled at one-minute intervals. This was necessary to prevent spatial and temporal aliasing. The water column structure changed relatively rapidly at this study site, driven by both horizontal advection and modulation of vertical structures by internal waves. Telemetry connected the acoustic sensors and our shore station in Aptos. This allowed us to receive, archive, process and distribute the data very quickly. When sampling was being undertaken near the location of one of our TAPS-6 sensors, we normally used a 30 sec sampling rate, communicating a layer's depth, thickness, rates of rising or sinking, and other relevant environmental descriptors to a sampling team on a ship by radio.

WORK COMPLETED

The data acquisition phase of this project was successfully completed on 31 July 2006. We also served as the small boat coordinator for the LOCO program in both 2005 and 2006, and the gear deployed by our three boats was all successfully recovered. The data collected by BAE Systems personnel were archived and transferred to the University of Rhode Island for use in the data analysis and synthesis tasks to follow, as well as for use in preparing presentations and manuscripts for publication.

RESULTS

Our TAPS-6 sensors began measuring multi-frequency volume scattering strength data at 1800 PDT on July 11, 2006 (Fig. 2). The strongest scattering each day was just below the sea surface, and was correlated with increased winds during the early evening. Whether the scattering was due to bubbles injected by breaking waves, to mixing of zooplankton and bubble-bearing fish larvae into the water column, or to both, remains an open question. At the beginning of our deployment, a thin, weak, sound scattering layer was observed near the pycnocline. Volume scattering strengths in the thin layer averaged about -60 dB at 420 kHz. This thin layer was strongly modulated in depth by an internal wave field. The acoustical scattering layer was *ca*. 1 to 2 m thick. It appeared to be relatively diffuse in its thickness, but was comparable in overall character to layer structures we observed at the same location in 2002. A similar layer was intermittently observed for varying periods throughout the period from July 11 through the end of our work at this station on July 29.

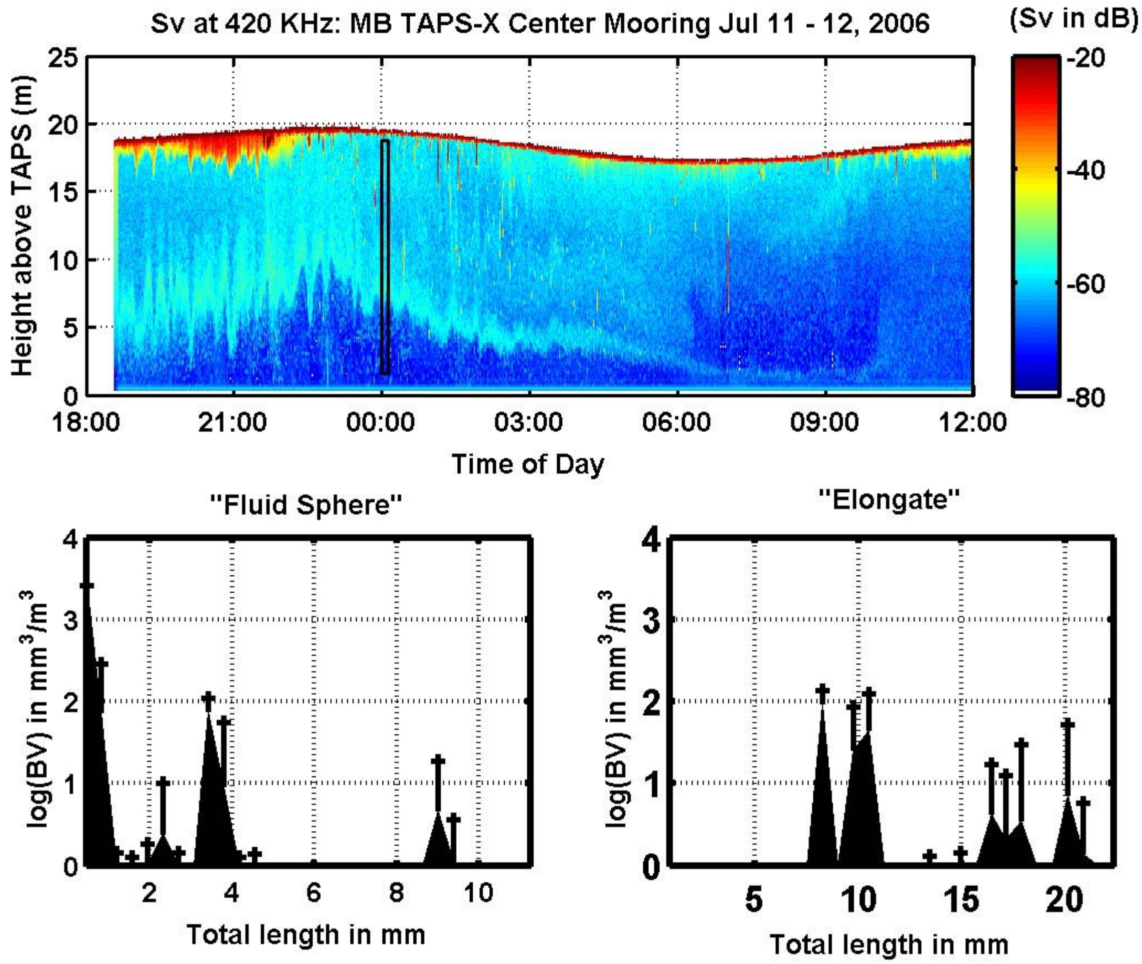

Figure 2: A TAPS-6 420 kHz record of volume scattering strength vs depth between 1800 PDT on July 11 and noon on July 12 revealed the presence of a thin scattering layer (top panel). The layer appeared to be modulated by internal waves and varied in depth over much of the 20 m deep water column. An inverse calculation for a small time interval and range of depths (see black box in top panel at midnight) showed that several sizes of scatterers were present for the two plankton shapes modeled (bottom left and bottom right panels). The first shape was a "fluid sphere" that was used to simulate scattering from small mesozooplankton such as fish and copepod eggs, small copepods, ostracods, etc. Organisms that scattered sound in a manner similar to " fluid spheres" were present at several sizes, the most abundant was for diameters of 0.25 – 0.75 mm. When summed over size, the mean biovolume in the box outlined in the top panel was 3,191 mm^3/m^3. A scattering model for elongate scatterers such as krill or mysids was also used in the inverse calculations, revealing even lower abundances of scatterers with elongate shapes. The average biovolume of elongate scatterers in the outlined box was only 173 mm^3/m^3. The lengths of the elongate scatterers present were 8, 10, 17, and 20 mm.

The thin scattering layer illustrated in Fig. 2 was usually seen in mid-water, but occasionally disappeared from view below the depth of the TAPS transducer face, nominally *ca*. 1.5 m above the seabed. This layer also occasionally appeared to approach the sea surface, disappearing from view within a few tens of cm of the air-water interface. Sometimes thin, the scattering layer occasionally

dispersed vertically, often filling most of the water column. Most of the biomass in the water column was best fit by a fluid sphere model (i.e., small copepods) with lengths < *ca*. 1 mm. However, the elongate scatterers in, and above the acoustical scattering layer were distinctly different in size. Above the layer, elongate organisms were 8 mm long. Within the scattering layer, i.e, between 6 m and 8 m above the TAPS, the organisms were 10 mm long (Fig. 3).

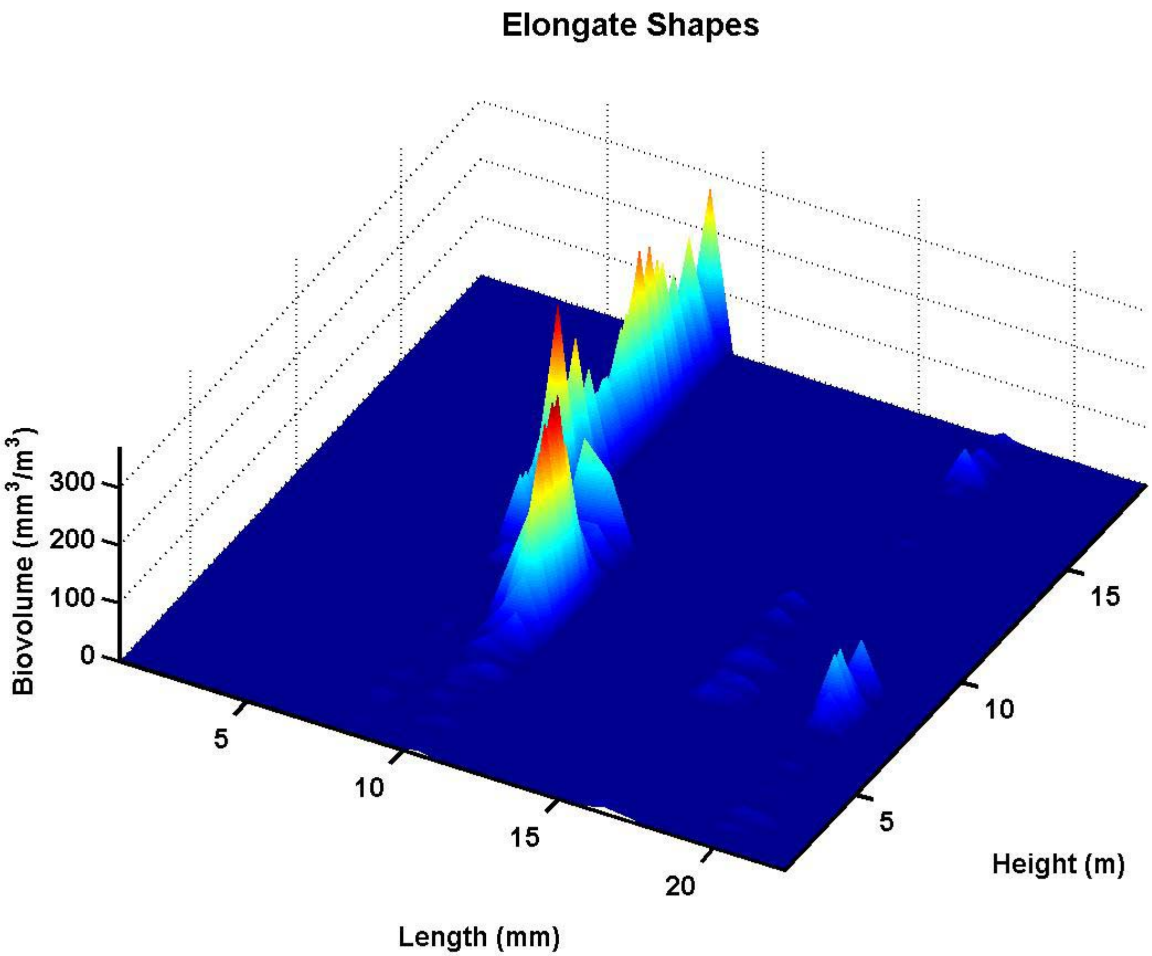

Figure 3: The inverse calculation for the box delineated in the top panel of Fig. 2 reveals a distinct difference in the sizes of the elongate scatterers above and within the acoustical scattering layer. In this figure, at the depth of the scattering layer for 420 kHz at midnight on July 11-12, most of the biovolume for the elongate scatters was found to be in the 10 mm size bin. Although there was a minor overlap in depth, most of the biovolume contributed by the elongate scatterers above the 420 kHz scattering layer was from organisms only 8 mm in length. The acoustical layer also received minor contributions from elongate scatterers that were ca. 17 and 21 mm in length.

Two days into the LOCO 2007 experiment, the character of high frequency acoustic scattering in the water column changed to one dominated by patterns of reverse vertical migration (Fig. 4). Normal vertical migration patterns involve a diel behavior rhythm, with organisms swimming toward the sea surface at sunset and returning to their normal daytime habitat in deeper water at sunrise. The reverse

vertical migration we observed has been previously described for zooplankton elsewhere (e.g., *Psuedocalanus spp.*, Ohman *et al.* 1983), although the present acoustic records provide more detail.

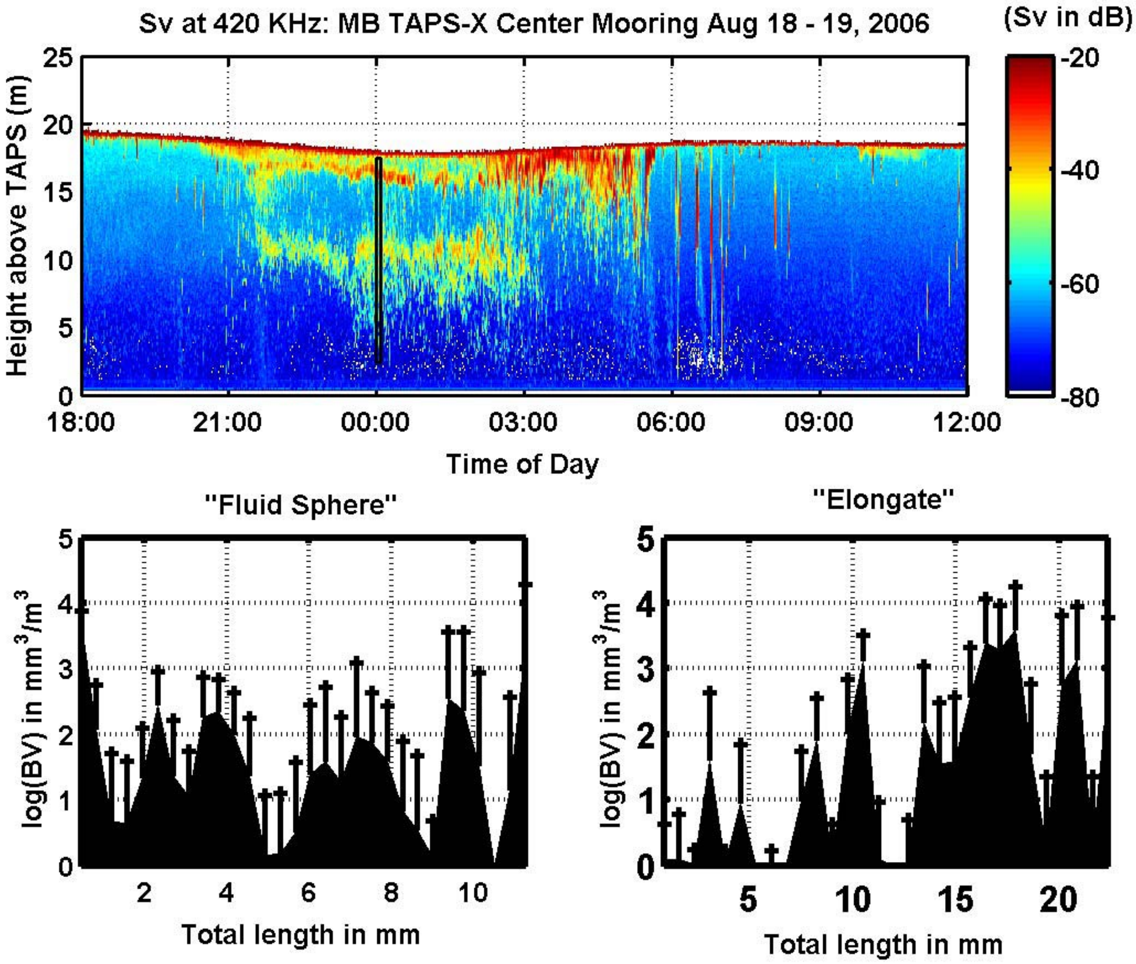

Figure 4: A TAPS-6 420 kHz record of volume scattering strength between the hours of 1800 PDT on July 18 and noon on July 19 revealed scattering layers that appeared just below the sea surface just before sunset (top panel). At sunset, the layers rapidly descended into the water column. One stopped at a depth of about 2 m, and the other continued downward until it reached about 9.5 m. Beginning at about 0300 PDT, the deeper layer gradually rose toward the surface, merging briefly with the upper layer before both rose to within a few tens of cm of the surface at ca. 0530 PDT. Small aggregations of scatterers, likely schools of small epipelagic fish, appeared to form between the surface and about 10 m depth between 0600 and 0800 PDT. In the bottom panels, an inverse calculation for a brief interval near midnight is displayed, and reveals the presence of numerous sizes of both elongate and quasi-spherical scatterers. Later in the month we were able to obtain qualitiative samples of the layer at 10 m with a net. The dominant zooplankter was Evade spp., but other copepods, e.g., Acarta tonsa, were present in low numbers. Although we captured only three mysids, our simple sampling methods would have allowed most micronekton to evade capture. Even so, the three specimens we did capture were of appropriate sizes to have explained the three peaks in biovolume between ca. 8-20 mm.

After July 12, the scattering was characteristic of a reverse migration in which most of the scattering organisms were located just under the surface during the day. At sunset, one or more layers would descend into the water column, where they would remain until between 0200 and 0500 PDT. During that interval the layers would gradually appear to diffuse and move towards the surface, usually arriving long before sunrise. When reverse vertical migration occurs, there is usually a presumption that the organisms are leaving the surface to forage, although the behavior also changes exposure to predation.

Six hour scattering records collected at the beginning and in the middle of July 2007 are provided to contrast periods during which the scattering in the water column was dominated by a thin layer structure (Fig. 2) and a time interval when reverse migration was present (Fig. 4). There were also days when both water column structures were seen simultaneously. Thin layer formation was not completely consistent during the periods when reverse migration occurred. Sometimes the upper half of the water column would simply be "filled" with downward migrators without the clear coalescing of distinct thin layers. The observed patterns were reminiscent of similar patterns observed in Aug / Sept at this site during 2005. Weak episodes of emergence and re-entry from and to the seabed were occasionally obseved (e.g., Abello *et al.* 2005), but there did not appear to be a strong correlation with either light or tides. A short net tow during the day revealed the presence of very small numbers of copepods within 0.5 m of the surface, tentatively identified as *Acartia tonsa*.

Data from other TAPS deployed in the area near the one for which the figures above were taken revealed patterns sufficiently similar to convince us that the temporal patterns of vertical distribution in this area were correlated over horizontal distances of at least 2 km, and that reverse vertical migration was the dominant process leading to zooplankton aggregation at particular depths. The observed acoustical backscattering was consistent with different proportions of small copepod-shaped and large elongate zooplankton in different layers. Most of the night-time zooplankton biomass originated from the surface waters, with much lower amounts episodically emigrating from the seabed. In contrast to 2002, during the same month, daytime thin zooplankton layers were largely absent or contained relatively little biomass. The layers that were present sometimes met the criteria for "thin layers" in Dekshenieks *et al.* 2001, but often they could be seen to gradually diffuse into the water column, technically not meeting the criteria for true "thin layers" for long periods before forming into another thin layer.

IMPACT/APPLICATIONS

Taken together, the data collected during 2002, 2005 and 2006 in Monterey Bay strongly suggest that fine-scale vertical structures and diel vertical migrations by the plankton are ecologically significant. As aggregating mechanisms they impact food availability for several trophic levels, but especially for larval organisms before they are able to swim in order to forage effectively. In 2007 we collected a time series that reveals changes in thin layer structures over several weeks. When these data are examined in the light of several data sets (e.g., phytoplankton and chl-a profiles, plankton species, small scale physical oceanography, etc.) collected by our co-PIs in LOCO, numerous questions that cut across physical and biological forcing in the coastal ecosystem can be addressed. The LOCO data are truly unique, with several components resulting from sampling that was specifically directed to observed phenomena as a result of having real-time data from the TAPS and ORCAS variants deployed by the BAE Systems and URI teams. The distribution of marine life at all trophic levels impacts current and future naval systems, especially those used in shallow water, where both mine detection and clearing operations must be conducted prior to engaging in expeditionary warfare. The

abundance and distribution of marine life also plays an as yet poorly understood role in controlling reverberation statistics at lower acoustic frequencies through food web interactions.

TRANSITIONS

Some of the multi-frequency technology we developed under sponsorship of ONR has been transitioned to operation in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). An 8-frequency sensor is currently moored in the Bering Sea, where it has been measuring volume scattering data via the Iridium system every 20 minutes from a depth of 17 m, and reporting it to PIs ashore hourly since late-April, 2007. This mooring will be retrieved in late September before the ice covers the shelf area. The acoustical volume scattering strength data are being processed to estimate abundances of zooplankton and micronekton for use in trophic models for the area. This system was moored from mid-April until the end of September in the same location in 2006. The Bering Sea supports one of the most economically valuable fisheries in the US EEZ. Estimates are that between 40 and 50% of the fish consumed in the US come from fisheries in that ocean area. The present deployment follows multi-month deployments on moorings by NOAA in the Coastal Gulf of Alaska in 2002, '03 and '04. Those data revealed continuing declines in North Pacific zooplankton biomass (Napp, *et al.* 2004; Holliday *et al.* 2005a; Holliday *et al*. 2005b; Bond *et al*. 2006).

RELATED PROJECTS

We consulted with NOAA and PMEL personnel in support of the transition discussed above. This consulting effort was funded under NOAA Contract AB133F05SU3288.

REFERENCES

Abello, H.U., S.M. Shellito, L.H. Taylor, and P.A. Jumars. 2005. Light-cued emergence and re-entry events in a strongly tidal estuary. Estuaries 28(4): 487-499.

Bond, Nicholas A., D.V. Holliday, Calvin W. Mordy, Jeffrey M. Napp and Phyllis J. Stabeno. 2006. Linkages between physical conditions in the coastal Gulf of Alaska and zooplankton biomass and size composition during 2002-04. PICES/GLOBEC Symposium (Poster T2-2684).

Dekshenieks, Margaret M., Percy L. Donaghay, James M. Sullivan, Jan E. B. Rines, Thomas R. Osborn, and Michael S. Twardowski. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. Marine Ecology Progress Series 223: 61–71.

Holliday, D.V. 1977. Extracting Bio-Physical Information from the Acoustic Signatures of Marine Organisms. In *Ocean Sound Scattering Prediction*, N.R. Anderson and B.J. Zahuranec, Eds. Marine Science Series Vol. 5, Plenum Press, New York, NY, pp. 619 - 624.

Holliday, D.V. and R.E. Pieper. 1980. Volume scattering strengths and zooplankton distributions at acoustic frequencies between 0.5 and 3 MHz. J. Acoust. Soc. Am. 67: 135-146.

Holliday, D.V., J.M. Napp, C.F. Greenlaw and P.J. Stabeno. 2005a. Interannual comparisons of zooplankton biomass in the Gulf of Alaska using bioacoustical sensors. PICES (Poster)

Holliday, D.V., J.M. Napp, C.F. Greenlaw and P.J. Stabeno. 2005b. Intra- and inter-annual comparisons of zooplankton biomass in the Gulf of Alaska using bioacoustical sensors. J. Acoust. Soc. Am. 118(3): 1908. (A).

Napp, J.M., C.F. Greenlaw, D.V. Holliday and P.J. Stabeno. 2004. Advection of shelf zooplankton in a predominantly down-welling ecosystem: Bioacoustic Detection of the dominant modes of variability. (PICES Poster)

Ohman, M.D., B.W. Frost, and E.B. Cohen. 1983. Reverse diel vertical migration: An escape from invertebrate predators. Science 220 (4604): 1404-1406.

PUBLICATIONS

Anderson, John, Van Holliday, Rudy Kloser, Dave Reid and Yvan Simard (Eds.). 2007. *Acoustic Seabed Classification of Marine Physical and Biological Landscapes.* ICES Cooperative Research Report, Rapport des Recherches Collectives, No. 286. 183 pp. [referred].

Anderson. John T., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard. 2007. Chapter 10: Future directions for acoustic seabed classification science. In *Acoustic Seabed Classification of Marine Physical and Biological Landscapes.* John T. Anderson, Ed., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp.139-146. [refereed].

Anderson, J.T., D. V. Holliday, R. Kloser, D. Reid, and Y. Simard. Acoustic Seabed Classification: Current Practice and Future Directions. ICES Journal of Marine Sciences. [submitted, refereed].

Cheriton, Olivia M., Margaret A. McManus, D.V. Holliday, Charles F. Greenlaw, Percy L. Donaghay, and Tim Cowles. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the west coast of the U.S. Estuaries & Coasts [in press, refereed].

Holliday, D.V. 2007. Chapter 2: Theory of sound scattering from the seabed. In *Acoustic Seabed Classification of Marine Physical and Biological Landscapes.* John T. Anderson, Ed., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp. 7-28. [refereed].

Holliday, D.V., J.M. Napp, C. Greenlaw, and P.J. Stabeno. Autonomous Zooplankton Sampling for Ocean Observing Systems. In *Topical Studies in Oceanography*, H. Batchelder (Ed.). Deep Sea Research II. [submitted, referred].

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. In *The American Institute of Fisheries Research Biologists' 50th Anniversary Proceedings*, Richard Beamish and Brian Rothschild (Eds). [submitted, referred].

Holliday, D.V., J.M. Napp, C. Greenlaw, and P.J. Stabeno. Autonomous Zooplankton Sampling for Ocean Observing Systems. In *Topical Studies in Oceanography*, H. Batchelder (Ed.). Deep Sea Research II. [submitted, refereed].

HONORS/AWARDS/PRIZES

In 2006 NOAA named a new 32' coastal research vessel the R/V D.V. Holliday. This vessel can sleep up to four persons and is configured to operate up to 100 nm offshore. Instrumentation currently includes Simrad EK60 multi-frequency echosounders (38, 70, 120 and 200 kHz) and a Simrad SM20/SM2000 200 kHz multi-beam sonar. Additional scientific gear includes passive acoustic sensors, an ROV and an AUV, underwater video, a Seabird SBE19+ CTD, a WeatherPak 2000 weather station, an IKMT plankton net, and a NOAA shipboard computing system. Her homeport is in San Diego, CA, and the vessel is currently used for advanced research in fisheries and plankton acoustics, as well as for routine fisheries acoustic surveys along the US Pacific coast.